Fast lifetime measurements of infrared emitters using a low-jitter superconducting single-photon detector

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We use a superconducting single-photon detector with less than 40 Hz dark count rate to measure spontaneous emission lifetimes of quantum wells emitting light at wavelengths of 935 and 1245 nm. The timing jitter of the measurement system—which includes the detector and all other electronic and optical components—is 68 ± 3 ps. We demonstrate how the infrared sensitivity and Gaussian temporal response function of this superconducting detector present clear advantages over conventional detector technologies. [DOI: 10.1063/1.2221516]

Low-noise, low-jitter photodetectors with single-photon counting capability at infrared wavelengths are a key enabling technology for a variety of scientific applications. For example, improved detectors at telecommunications wavelengths are of crucial importance to the burgeoning field of quantum cryptography, in extending the range and speed of fiber-based quantum key distribution systems.[1] Such detectors would also be invaluable in range-finding applications such as eye-safe light detection and ranging (LIDAR) imaging and fault location in optical fibers. In this letter, we focus on the potential of these detectors for materials characterization when measuring spontaneous emission lifetimes using time-correlated single-photon counting (TCSPC).[2]

TCSPC is a powerful technique for studying weakly emitting sources such as a single molecule or a single quantum dot, because it uses detectors—typically avalanche photodiodes (APDs) or photomultiplier tubes (PMTs)—that can be triggered by a single photon. For visible wavelengths, low-jitter detectors and fast electronics have lowered the time resolution of TCSPC systems to near 20 ps.[2] However, advances in the infrared region have been more modest, because silicon APDs and most PMTs are insensitive for wavelengths longer than 1 μm. APDs based on InGaAs or Ge can have reasonable detection efficiencies in the infrared, but suffer from afterpulsing and very high dark count rates[3,4] unless gated to run at very low repetition rates;[5] as a result, the available dynamic range is limited, especially for inefficient sources.

The fastest Si APDs and microchannel plate PMTs have temporal instrument response functions (IRFs) with full width at half maxima (FWHM) between 20 and 30 ps.[2] However, these IRFs do not have Gaussian profiles and are typically plagued by long exponential tails.[3,6] Dual-junction Si APDs offer improved temporal response shapes,[3,6] but are not sensitive to wavelengths beyond 1 μm. As a further complication, the avalanche photodetection process in APDs is sometimes accompanied by photon emission; thus, quantum communication systems that employ APDs have an increased vulnerability to eavesdropping.[7]

Recently, superconducting single-photon detectors (SSPDs) have been developed that can offer considerable advantages over conventional detectors.[8–11] SSPDs have been demonstrated with up to 20% quantum efficiency at visible wavelengths, low dark count probability, the capacity for gigahertz counting rates, and sensitivity well into the infrared.[8–10] Initial measurements indicate that these detectors should be good candidates for use in TCSPC systems, with reports of timing jitter as low as 18 ps.[8,9]

Here, we implement an SSPD in a TCSPC scheme to measure the spontaneous emission lifetimes of semiconductor quantum wells (QWs) that emit in the infrared. We show that, unlike conventional Si APDs, the temporal response function of this SSPD has a Gaussian shape, offering a dramatic advantage for measurements of spontaneous emission lifetime. We also demonstrate the superconducting detector's utility for a wavelength of 1245 nm, well outside the range of silicon detectors.

Figure 1 shows a schematic of the experiment. A QW sample is optically pumped with a Ti:sapphire laser that produces ~1 ps pulses with a center wavelength of 780 nm at an 82 MHz repetition rate. Photoluminescence from the sample is collected with an objective lens, spectrally filtered by a monochromator, and coupled into a single-mode fiber for transmission to the SSPD inside the cryocooler. Alternatively, the monochromator output can be diverted to a Si

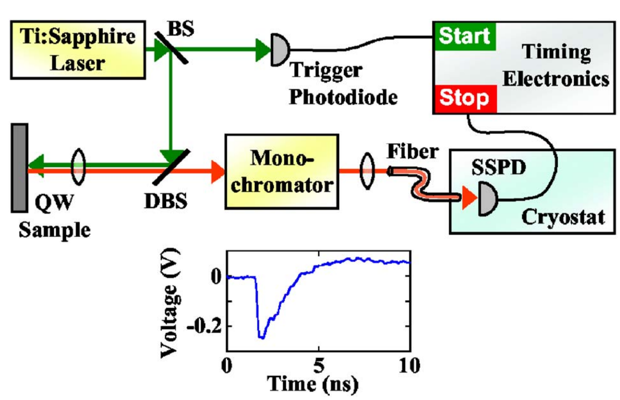

FIG. 1. (Color online) Experimental geometry. BS is a beamsplitter and DBS is a dichroic BS. The lower plot shows a voltage pulse from the SSPD.

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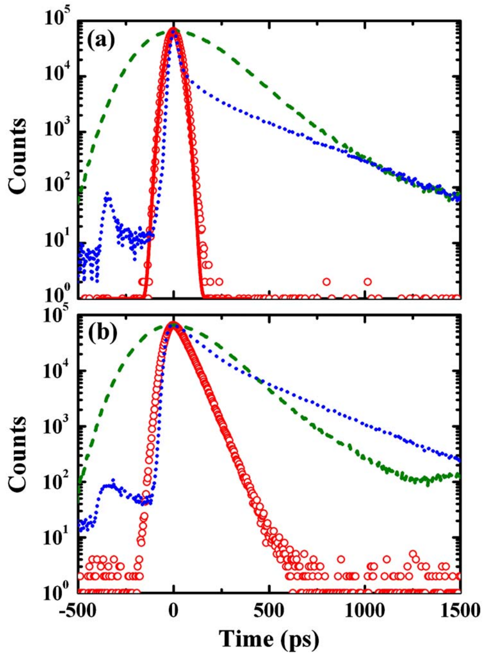

FIG. 2. (Color online) (a) Instrument response functions of three detectors: SSPD (red open circles), conventional Si APD (dashed green curve), and fast Si APD (dotted blue curve). The solid red curve is a Gaussian fit to the measured SSPD response function. (b) Lifetime measurement of emission at 935 nm from a GaAs/InGaAs quantum well with these three detectors.

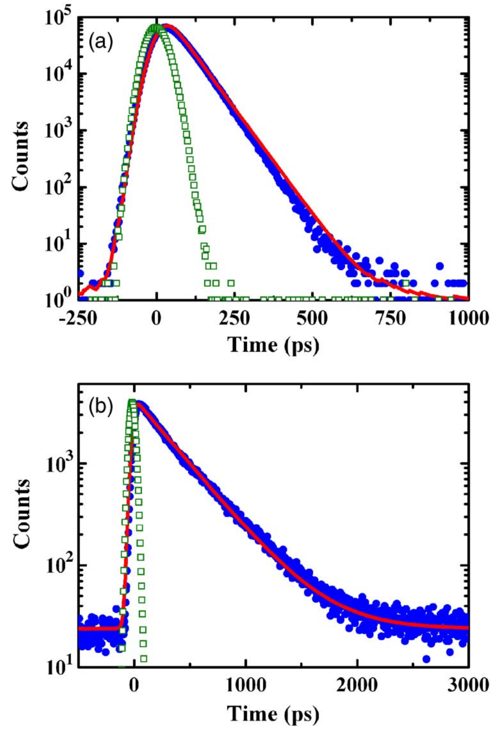

FIG. 3. (Color online) SSPD lifetime measurements: IRF (open green squares), measured decay (closed blue circles) and fit (solid red curve) for (a) QW1 at 935 nm and (b) QW2 at 1245 nm.

APD by inserting a mirror before the fiber coupler (not shown).

Since the superconducting detector must be operated at temperatures near 4 K, we have packaged the device in a practical, cryogen-free system using a commercially available cryocooler.[11] The SSPD consists of a 100 nm wide wire of superconducting niobium nitride covering a $10\times10\ \mu\text{m}^2$ area with a serpentine meander. When this current-biased wire absorbs a photon, it momentarily creates a nonsuperconducting hot spot, forming a voltage drop across this resistive section of the track and sending a high-speed voltage pulse (see Fig. 1) down a transmission line.[10,12] For the bias conditions used here, the SSPD exhibits no measurable afterpulsing.

After sufficient amplification, this pulse is sent to the TCSPC electronics, where the 82 MHz clock signal from the fast photodiode starts a timer and the SSPD pulse stops it. The stop rate is kept less than 82 kHz to ensure an average of less than 1 count per 1000 pulses, preventing a pileup of counts in the early time bins.[2] The start and stop inputs to the electronics each pass through a constant fraction discriminator before engaging a digital time-to-amplitude converter (TAC). The TAC output is fed into a multichannel analyzer, which builds up count versus time histograms like those in Figs. 2 and 3. The electronics introduce time jitter of less than 30 ps, which should add in quadrature with any jitter from the detector.[2]

To measure the IRF of a detector, we tune the monochromator to 780 nm and heavily attenuate the laser beam. The results are shown in Fig. 2(a). The SSPD's response is fitted well—over nearly five decades of dynamic range—by a Gaussian with a FWHM of 71 ps. Averaging several measurements yields a timing jitter of 68 ± 3 ps FWHM for the entire measurement system—including all optical and electronic components.[13] This jitter is independent of count rate between 50 Hz and 1 MHz.

While timing jitter as low as 18 ps has been reported for similar SSPD devices, these previous measurements were done in a regime where the detector produced a voltage pulse for *every* incident laser pulse.[8,9] Here, by contrast, we report jitter measurements for the much lower count rates required for TCSPC. Differences in our device, amplifier, or timing electronics may also contribute to this discrepancy with previous work.

For comparison, Fig. 2(a) also shows the measured IRFs of a conventional silicon APD (FWHM$\approx$400 ps) and a fast Si APD (FWHM$\approx$40 ps). Although the fast APD has a narrow main peak, it also has an exponential tail that persists for hundreds of picoseconds. This diffusion tail, which is typical of APDs, is caused by the slow diffusion of photoexcited carriers from the neutral region into the high-field region of the device.[3] The relative magnitudes of the main peak and tail—and thus the shape of the total IRF—depend strongly on wavelength, further complicating the analysis of measured decay curves.[3,14]

The advantage of the SSPD over the Si detectors is evident in Fig. 2(b), which shows lifetime measurements of a GaAs/InGaAs quantum well (QW1). This sample has an emission peak at 935 nm and was chosen for its relatively short lifetime. Only the SSPD-measured lifetime clearly shows a clean single-exponential decay, even without deconvolving the IRF. Although the SSPD has a fairly low detection efficiency ($\sim$2% at 900 nm including fiber coupling losses),[11] its low dark count rate (here $\sim$20–40 Hz) allows measurements with several decades of dynamic range simply by increasing the integration time (still under 3 min here). In addition, identification of multiexponential processes should be far more straightforward with the SSPD's Gaussianshaped IRF than with either Si APD's multicomponent response.

Figure 3(a) plots the SSPD IRF and decay data from Fig. 2, along with a fit. This fit is the measured IRF convolved with an exponential with a 58 ps decay constant. Figure 3(b) shows similar data for a GaAs/GaInNAs double QW (QW2) emitting at 1245 nm: here the fit has a decay time of 333 ps. The data in Fig. 3(b) could not have been acquired using either of the Si APDs used in Fig. 2, since this wavelength is well outside the photosensitive range of silicon. Note that the use of this SSPD is not limited to QWs, which can produce strong photoluminescence. For example, we recently demonstrated that this device is sensitive enough to measure the spontaneous emission lifetime of a single quantum dot.[11]

In summary, we have demonstrated the use of a superconducting single-photon detector in a time-correlated single-photon counting measurement system. Unlike conventional silicon APDs, this detector has a Gaussian temporal response function, which is clearly advantageous for determining short lifetimes or analyzing multiexponential decays. In addition, the superconducting detector is sensitive to wavelengths longer than 1 μm, which silicon detectors are not. With these advantages, superconducting detectors like this one should have many practical uses, from characterizing weakly emitting materials and fiber-based quantum key distribution to a host of other applications requiring high time resolution and single-photon sensitivity in the infrared region of the spectrum.

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